

## DUST IN THE DIFFUSE EMISSION OF THE GALACTIC PLANE: THE *HERSCHEL*/*SPITZER* SPECTRAL ENERGY DISTRIBUTION FITTING\*

M. COMPIÈGNE<sup>1</sup>, N. FLAGEY<sup>2</sup>, A. NORIEGA-CRESPO<sup>2</sup>, P. G. MARTIN<sup>1,3</sup>, J.-P. BERNARD<sup>4</sup>, R. PALADINI<sup>2</sup>, AND S. MOLINARI<sup>5</sup>

<sup>1</sup> Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St. George Street, Toronto, ON M5S 3H8, Canada; [compiegne@cita.utoronto.ca](mailto:compiegne@cita.utoronto.ca)

<sup>2</sup> Spitzer Science Center, California Institute of Technology, 1200 East California Boulevard, MC 220-6, Pasadena, CA 91125, USA

<sup>3</sup> Department of Astronomy and Astrophysics, University of Toronto, 50 St. George Street, Toronto, ON M5S 3H4, Canada

<sup>4</sup> Centre d'Étude Spatiale des Rayonnements, CNRS et Université Paul Sabatier-Toulouse 3, Observatoire Midi-Pyrénées,  
9 Av. du Colonel Roche, 31028 Toulouse Cedex 04, France

<sup>5</sup> INAF-Istituto Fisica Spazio Interplanetario, Via Fosso del Cavaliere 100, I-00133 Roma, Italy

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### ABSTRACT

The first *Herschel* Hi-Gal images of the Galactic plane unveil the far-infrared diffuse emission of the interstellar medium with an unprecedented angular resolution and sensitivity. In this Letter, we present the first analysis of these data in combination with those of *Spitzer* GLIMPSE and MIPS GAL. We selected a relatively diffuse and low excitation region of the  $l \sim 59^\circ$  Hi-Gal Science Demonstration Phase field to perform a pixel-by-pixel fitting of the 8 to 500  $\mu\text{m}$  spectral energy distribution (SED) using the DustEM dust emission model. We derived maps of the very small grain (VSG) and polycyclic aromatic hydrocarbon (PAH) abundances from the model. Our analysis allows us to illustrate that the aromatic infrared band intensity does not necessarily trace the PAH abundance but rather the product of “abundance  $\times$  column density  $\times$  intensity of the exciting radiation field.” We show that the spatial structure of PACS 70  $\mu\text{m}$  maps resemble the shorter wavelengths (e.g., IRAC 8  $\mu\text{m}$ ) maps, because they trace both the intensity of exciting radiation field and column density. We also show that the modeled VSG contribution to PACS 70  $\mu\text{m}$  (PACS 160  $\mu\text{m}$ ) band intensity can be up to 50% (7%). The interpretation of diffuse emission spectra at these wavelengths must take stochastically heated particles into account. Finally, this preliminary study emphasizes the potential of analyzing the full dust SED sampled by *Herschel* and *Spitzer* data, with a physical dust model (DustEM) to reach the properties of the dust at simultaneously large and small scales.

**Key words:** dust, extinction – infrared: ISM – methods: data analysis

**Online-only material:** color figures

### 1. INTRODUCTION

The first *Herschel* (Pilbratt et al. 2010) images of the galactic plane obtained during the Science Demonstration Phase (SDP) reveal the far-infrared diffuse emission of the interstellar medium (ISM) with unprecedented beauty and detail. The Hi-Gal project (Molinari et al. 2010) provides an unbiased photometric survey of the inner Galactic plane emission between 70 and 500  $\mu\text{m}$  where the spectral energy distribution (SED) is dominated by the largest dust grains ( $a \sim 0.1 \mu\text{m}$ ). Combined with the *Spitzer* GLIMPSE (Churchwell et al. 2009) and MIPS GAL (Carey et al. 2009) surveys that cover the dust SED from 3.6 to 24  $\mu\text{m}$ , light mostly emitted by the smallest grains ( $a \lesssim 10 \text{ nm}$ ), we will for the first time reliably sample the full dust SED of the diffuse emission at all spatial scales down to  $\sim 40''$  and over a large fraction of the Galactic plane.

At 70 and 160  $\mu\text{m}$ , many of the observed structures show a close spatial correlation with some of the classical infrared tracers of small dust particles, like the emission measured at 8 and 24  $\mu\text{m}$ , and therefore, one expects a partially similar origin and/or a similar dependence on ISM physical properties. To properly understand the origin of this emission is the first step of the data analysis.

Dust is heated by stellar ultraviolet (UV)–visible photons and re-radiates the absorbed energy in the infrared. Assuming some dust properties, this dust emission is widely used to trace crucial

quantities like cloud masses or star-forming activity. However, to accurately derive these quantities requires taking into account the dust properties’ evolution, how it affects its emission, and how it reflects the ISM properties. On the other hand, dust plays a crucial role for the ISM physics and chemistry. Since dust and the rest of ISM are tightly interlocked, changes on the dust properties affect those of the gas phase. It is then necessary to characterize the physical processes responsible for the dust evolution to assess their role within the ISM life cycle and to be able to use dust as a reliable tracer of the ISM. Accessing the full dust SED over a large fraction of the sky allows us to follow the behavior of every dust component over a broad range of physical conditions which is invaluable information for the study of dust evolution.

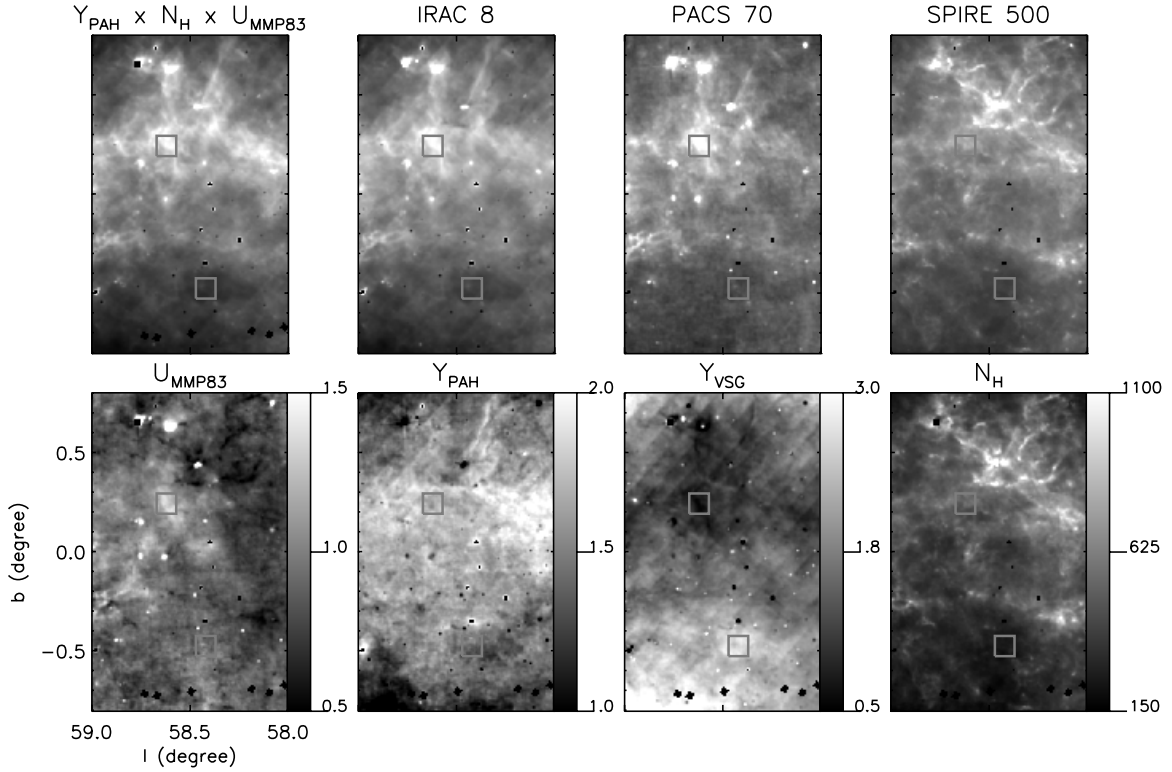
In this Letter, we present the first analysis of the Hi-Gal data combined with that of GLIMPSE and MIPS GAL to obtain the full dust SED from 8 to 500  $\mu\text{m}$ . In Section 2, we describe the observations and the fitting method that makes use of a physical dust model, DustEM<sup>6</sup> (Compiegne et al. 2010). In Section 3, we present and discuss the results and how our analysis method allows us to better interpret the behavior of extended emission observed with the *Herschel*/*Spitzer* photometers. We conclude in Section 4.

### 2. OBSERVATIONS AND ANALYSIS METHOD

Two fields were observed (at  $l \sim 30^\circ$  and  $l \sim 59^\circ$ ) during the SDP as part of the Hi-Gal program with PACS 70 and 160  $\mu\text{m}$  and all of the SPIRE channels (Molinari et al. 2010).

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<sup>6</sup> To be found at <http://www.ias.u-psud.fr/DUSTEM>.



**Figure 1.** IRAC 8  $\mu\text{m}$ , PACS 70  $\mu\text{m}$ , and SPIRE 500  $\mu\text{m}$  maps. The obtained maps for the fitted parameters are  $Y_{\text{PAH}}$ ,  $Y_{\text{VSG}}$ ,  $N_{\text{H}}$ , and  $U_{\text{MMP83}}$ . Also shown is a map of the product  $Y_{\text{PAH}} \times N_{\text{H}} \times U_{\text{MMP83}}$ . The two boxes delineate the areas used to obtain the spectra of Figure 2. Note that the black spots are due to pixel masking (e.g., 8  $\mu\text{m}$  point sources).

For this study, to satisfy the assumptions made in the model we describe below, we focus on a subfield of the  $l \sim 59^\circ$  field that shows no obvious H II regions or young star cluster and that is relatively diffuse regarding the rest of the  $l \sim 59^\circ$  field and the  $l \sim 30^\circ$  field. We also avoid the higher latitudes ( $|b| \gtrsim 0.8$ ) that display weak intensity where *Herschel* data could be less reliable at this early stage of data processing. The maps were obtained with the ROMAGAL pipeline (Traficante et al. 2010). For PACS 160  $\mu\text{m}$ , SPIRE 250, 350, and 500  $\mu\text{m}$ , we applied the calibration described in Bernard et al. (2010). The gain uncertainty for these data is taken to be 20%. The zero level was corrected by cross-calibration with Planck data with absolute uncertainties of  $\pm 19.8$ , 14.6, 7.5, and 3.0  $\text{MJy sr}^{-1}$  at 160, 250, 350, and 500  $\mu\text{m}$ , respectively, which represent about half of the gain uncertainty for the faintest pixels of the studied region. We cross-calibrate the PACS 70  $\mu\text{m}$  data with the MIPS 70  $\mu\text{m}$  data from the MIPS GAL survey (R. Paladini et al. 2010, in preparation). We then apply the 15% gain uncertainty of MIPS 70  $\mu\text{m}$ . We also use the IRAC 8  $\mu\text{m}$  data from the GLIMPSE survey and the MIPS 24  $\mu\text{m}$  data from the MIPS GAL survey. The gain uncertainty for these two data sets is taken to be 10%. Point sources are subtracted from the IRAC 8  $\mu\text{m}$  data.

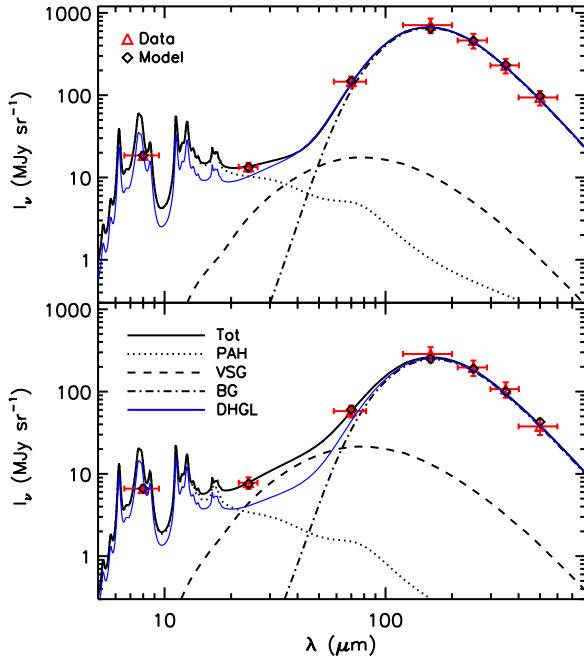
The zodiacal light contribution, important at shorter infrared wavelengths (Kelsall et al. 1998) has been removed from all the *Spitzer* data (on average, 1.1, 16.5, and 4.5  $\text{MJy sr}^{-1}$  at 8, 24, and 70  $\mu\text{m}$ , respectively) and then from the PACS 70  $\mu\text{m}$  following its cross-calibration on MIPS 70  $\mu\text{m}$ . We do not perform any subtraction of the zodiacal emission at longer wavelengths where its contribution is negligible ( $< 1 \text{ MJy sr}^{-1}$ ). We bring every map to the lowest resolution of the SPIRE 500  $\mu\text{m}$  one (FWHM  $\sim 37''$ ). We do this assuming a Gaussian point-spread function of appropriate width. We then project all maps into the SPIRE 500  $\mu\text{m}$  grid (pixel field of view  $\sim 11.5'$ ). Figure 1

displays the IRAC 8  $\mu\text{m}$ , PACS 70  $\mu\text{m}$ , and SPIRE 500  $\mu\text{m}$  maps.

We use the DustEM dust model described in Compiègne et al. (2010) to analyze the data. We consolidate the standard four grain populations into three: the polycyclic aromatic hydrocarbons (PAHs), small amorphous carbons representing the very small grains (VSGs), and we merged large amorphous carbons and silicates into a single big grains (BGs) population. Using the MPFIT (Markwardt 2009) IDL minimization routine,<sup>7</sup> we choose to adjust the following four parameters to fit the observed SED for each pixel: the (1) PAH and (2) VSG abundances relative to BGs,  $Y_{\text{PAH}}$  and  $Y_{\text{VSG}}$ , (3) the BG opacity,  $\tau_{\text{BG}}$ , and (4)  $U_{\text{MMP83}}$  a scaling factor of the “solar neighborhood” Mathis et al. (1983) (hereafter MMP83) exciting radiation field. Self-extinction along the line of sight can be significant at 8  $\mu\text{m}$  and is accounted for assuming  $I_\lambda = I_{0,\lambda} \frac{1-e^{-\tau_\lambda}}{\tau_\lambda}$ , where  $I_{0,\lambda}$  is the integrated emissivity and  $\tau_\lambda$  the total dust opacity that is computed from the dust model using  $Y_{\text{PAH}}$ ,  $Y_{\text{VSG}}$  and  $\tau_{\text{BG}}$ . Since in this first analysis we do not perform any separation of the components along the line of sight, the derived parameters result from the spatial mixing of different physical conditions. Fortunately, at  $l \sim 59^\circ$ , we expect only contributions from the Vulpecula star formation region ( $d \sim 2 \text{ kpc}$ ) and the Perseus arm ( $d \sim 8.5 \text{ kpc}$ ).

We focus on the behavior of the smallest particles (PAH and VSG) and hence, we do not assume any variation of the BG properties (i.e.,  $\tau_{\text{BG}}/N_{\text{H}} = \text{constant}$ ). In that case and to ease the following discussion, we can convert  $\tau_{\text{BG}}$  into the hydrogen column density,  $N_{\text{H}}$ , and assume the relative abundances of PAHs and VSGs,  $Y_{\text{PAH}}$  and  $Y_{\text{VSG}}$  to be their abundance relative to hydrogen. Indeed, emissivity and/or abundance of the BG is

<sup>7</sup> To be found at <http://purl.com/net/mpfit>.



**Figure 2.** Mean spectra over the boxes shown in Figure 1 and corresponding fitted model. The upper (lower) spectrum correspond to the northern (southern) box. For comparison, the blue lines show the spectra obtained for the fitted  $N_H$  and  $U_{MMP83}$  but for the reference diffuse high galactic latitude dust properties (DHGL,  $Y_{PAH}$ , and  $Y_{VSG} = 1$ ).

(A color version of this figure is available in the online journal.)

known to evolve (e.g., Stepnik et al. 2003; Désert et al. 2008) and can be studied using the *Herschel* data (see Paradis et al. 2010) but to take such variations into account is beyond the scope of this Letter.

Figure 2 illustrates the obtained fitted spectra for two observed SEDs. The photometric points computed from a modeled spectrum take into account the color corrections. Schematically, the 160, 250, 350, and 500  $\mu m$  photometric points give constraints on  $U_{MMP83}$  and  $\tau_{BG}$  ( $N_H$ ) through the BG emission. The shape of the BG SED depends on  $U_{MMP83}$  as this grain population is at thermal equilibrium, in contrast with the stochastically heated grains (PAHs and VSGs) whose SED shape is invariant regarding the radiation field intensity (see Draine & Li 2007; Compiègne et al. 2010). Hence, given  $U_{MMP83}$  the absolute level of the BG SED constrains  $N_H$ . Finally, the 8 and 24  $\mu m$  constrain the abundances of the two stochastically heated populations since the intensity of their emission scales as  $Y \times N_H \times U_{MMP83}$ .

### 3. RESULTS AND DISCUSSION

Figure 1 shows maps of the  $Y_{PAH}$ ,  $Y_{VSG}$ ,  $N_H$ , and  $U_{MMP83}$  parameters and a map of the product  $Y_{PAH} \times N_H \times U_{MMP83}$ .  $\chi^2_{\text{reduced}} \lesssim 2$  for all pixels over these maps.  $N_H$  is given in unit of  $10^{20} \text{ H cm}^{-2}$  and  $U_{MMP83}$  is dimensionless.  $Y_{PAH}$  and  $Y_{VSG}$  are given relative to the value for the diffuse high galactic latitude medium (DHGL;  $|b| \gtrsim 15^\circ$ ),  $M_{PAH}/M_H = 7.8 \times 10^{-4}$  and  $M_{VSG}/M_H = 1.65 \times 10^{-4}$  (see Compiègne et al. 2010). Note that  $M_{BG}/M_H = 9.25 \times 10^{-3}$ . The uncertainties on these parameters are given as computed in MPFIT from the covariance matrix.

The column density lies between  $\sim 1.5 \times 10^{22} \text{ H cm}^{-2}$  for the most diffuse part and  $\sim 1.1 \times 10^{23} \text{ H cm}^{-2}$  toward the dense filamentary structures, with a relative uncertainty of  $\sim 18\%$ .

The  $U_{MMP83}$  ranges between  $\sim 0.5$  and  $\sim 1.5$  with a relative uncertainty of  $\sim 22\%$ , which is consistent with the absence of young stellar cluster over our field. In agreement with the fact that the radiation field is shielded, we see that  $U_{MMP83}$  decreases toward the highest column density regions. These  $U_{MMP83}$  and  $N_H$  values are in agreement with previous estimates (see Bernard et al. 2010).  $Y_{PAH}$  goes from  $\sim 1.0$  to  $\sim 2.0$  with a relative uncertainty of  $\sim 16\%$ . The obtained  $Y_{VSG}$  spans a wider range than  $Y_{PAH}$ , going from  $\sim 0.5$  to  $\sim 3.0$  but with a relative uncertainty going from  $\sim 40\%$  for the highest values to  $\sim 60\%$  for the smallest values. The variations of these parameters over the map are therefore significant.

Figure 2 shows the averaged SED over the two boxes seen in Figure 1 and illustrate the wide  $Y_{VSG}$  variations. For the top (bottom) panel spectrum, we have  $N_H = 5.1 \pm 0.9 \times 10^{22} \text{ H cm}^{-2}$  ( $2.5 \pm 0.5 \times 10^{22} \text{ H cm}^{-2}$ ),  $U_{MMP83} = 1.2 \pm 0.2$  ( $0.9 \pm 0.2$ ),  $Y_{PAH} = 1.7 \pm 0.2$  ( $1.4 \pm 0.2$ ), and  $Y_{VSG} = 0.8 \pm 0.5$  ( $2.7 \pm 1.0$ ).

$Y_{PAH}/Y_{VSG}$  seems to vary at large spatial scales (decreases from  $b \sim 0.2$  to  $b \sim -0.7$ ) and also at the edge of some dense filaments (near the “chimney” region around coordinate 58.4, +0.55). Both  $Y_{PAH}$  and  $Y_{VSG}$  decrease toward some of the densest filamentary structures but it appears not to be systematic and could be biased by the too simplistic assumption made on the self-absorption. A decrease of the smallest dust abundance toward dense regions regarding the biggest grains was reported by previous work and was interpreted as the coagulation of these smallest particles together with the bigger ones (e.g., Stepnik et al. 2003; Flagey et al. 2009). Previous studies also reported a lack of correlation or even an anti-correlation between the aromatic infrared bands and the mid-IR continuum emission (interpreted as the evolution of small dust properties) at the illuminated ridge of molecular clouds (e.g., Abergel et al. 2002; Berné et al. 2007; Compiègne et al. 2008), toward high Galactic cirrus at the interface between atomic and molecular material (Miville-Deschênes et al. 2002) or at Galactic scale in the Large Magellanic Cloud (Paradis et al. 2009).

The spatial structure of SPIRE 500  $\mu m$  intensity, which is dominated by the BG contribution, is well correlated with  $N_H$ . Indeed,  $U_{MMP83}$ , and subsequently the BG temperature, are quite stable in our field so that the intensity variations at these wavelengths (Rayleigh tail of the blackbody-like emission) are dominated by the column density variations (assuming no BG emissivity variations). Comparing the 8  $\mu m$  and  $Y_{PAH}$  maps, it is striking that the aromatic infrared band (AIB) intensity does not directly trace the PAH abundance. PAHs are stochastically heated and the observed AIB intensity (i.e., IRAC 8  $\mu m$ ) then scales linearly with the product  $Y_{PAH} \times N_H \times U_{MMP83}$  as seen in Figure 1. The only difference is related to the extinction along the line of sight that can be seen in the IRAC 8  $\mu m$  (as dark filamentary structures correlated with the  $N_H$  map) and not in the  $Y_{PAH} \times N_H \times U_{MMP83}$  map. The PACS 70  $\mu m$  image shows a close spatial correlation with the classical infrared tracers of small dust particles, like the emission measured at 8  $\mu m$  (see Figure 1). The emission at 70  $\mu m$  is not due to a single dust component. As seen in Figure 2, in the framework of our model both the VSGs that are stochastically heated and the BGs that are at thermal equilibrium contribute to the emission at this wavelength. For  $U_{MMP83} \lesssim 100$ , the BG emission at 70  $\mu m$  fall in the Wien part of the blackbody like emission that makes it more sensitive to  $U_{MMP83}$  than at 500  $\mu m$ . Therefore, the two emission components (from VSGs and BGs) at 70  $\mu m$  are sensitive to both  $N_H$  and  $U_{MMP83}$  which better explains

correlation of this map with the  $8\,\mu\text{m}$  map (also sensitive to both  $N_H$  and  $U_{\text{MMP83}}$ ) as opposed to the  $500\,\mu\text{m}$  map (more sensitive to  $N_H$ ).

The model allows us to compute the relative contribution of the three dust populations in the different photometric bands. The VSG contribution to PACS  $70\,\mu\text{m}$  increases if the VSG abundance relative to BG increases and/or if  $U_{\text{MMP83}}$  decreases (shifting the BG emission toward longer wavelengths). In the studied field, the VSG contribution to the PACS  $70\,\mu\text{m}$  intensity goes from  $\sim 10\%$  up to  $\sim 50\%$  with a median value of  $\sim 27\%$ . The maximum contribution of VSGs to PACS  $100\,\mu\text{m}$  and PACS  $160\,\mu\text{m}$  is  $\sim 17\%$  and  $\sim 7\%$  (the median is  $9\%$  and  $3\%$ ), respectively. For the top (bottom) panel spectrum of Figure 2, the contribution is  $12\%$ ,  $4\%$ ,  $2\%$  ( $35\%$ ,  $13\%$ ,  $5\%$ ) for PACS  $70$ ,  $100$  and  $160\,\mu\text{m}$ , respectively. This result strongly suggests that the proper analysis of *Herschel* spectrum of diffuse emission including  $70\,\mu\text{m}$  may require to account for stochastically heated grains.

#### 4. SUMMARY AND CONCLUSION

We have presented the first analysis of the diffuse emission of the Galactic plane as observed by *Herschel* combining the Hi-Gal data with the GLIMPSE/MIPSGAL *Spitzer* data. Toward a subfield of the  $l \sim 59^\circ$  Hi-Gal SDP field, we performed a pixel-by-pixel fitting of the full dust SED between  $8$  and  $500\,\mu\text{m}$  using a physical dust emission model, DustEM (Compiègne et al. 2010).

Assuming that the BG properties remain constant, the unique wavelength coverage provided by the *Spitzer* and *Herschel* photometric observations allows us to derive the following parameters for our dust model: the PAH and VSG abundances,  $Y_{\text{PAH}}$  and  $Y_{\text{VSG}}$ , the column density,  $N_H$ , and the intensity of the exciting radiation field,  $U_{\text{MMP83}}$ . To our knowledge, this is the first time PAH and VSG abundance maps are derived using such a pixel-by-pixel SED fitting at resolution  $< 1'$  and over such an extended field. These abundances, as well as  $N_H$  and  $U_{\text{MMP83}}$ , vary significantly over the field. As already reported by previous studies,  $Y_{\text{PAH}}$  and  $Y_{\text{VSG}}$  appear not to be positively correlated.

Although it was already theoretically known, our analysis method provide a firm demonstration that IRAC  $8\,\mu\text{m}$  does not trace the PAH abundance but the product  $Y_{\text{PAH}} \times N_H \times U_{\text{MMP83}}$ .

We also showed that at  $70\,\mu\text{m}$ , the modeled emission is due to both the BGs and the VSGs. At these wavelengths, the BG emission is sensitive to both the intensity of the exciting radiation field and the column density is likewise sensitive to the VSG, explaining the similar spatial structure seen in PACS  $70\,\mu\text{m}$  maps regarding shorter wavelengths. Using our model, we derived the VSG contribution to the PACS channels that can be up to  $\sim 50\%$ ,  $\sim 17\%$ , and  $\sim 7\%$  at  $70$ ,  $100$ , and  $160\,\mu\text{m}$ , respectively. We conclude that the interpretation of *Herschel* spectrum of the diffuse emission down to  $70\,\mu\text{m}$  may require us to take into account the stochastically heated population (VSG).

Finally, our analysis allows for a better understanding of the first *Herschel* images of the Galactic plane diffuse emission by disentangling the different dust population contributions and also revealing the great potential of the *Herschel/Spitzer* synergy combined with a physical dust model for the study of dust evolution (see also Abergel et al. 2010).

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